FLUCTUATION OF BUNCH LENGTH IN BURSTING CSR: MEASUREMENT AND SIMULATION

P. Schönfeldt*, A. Borysenko, E. Hertle, N. Hiller, V. Judin, A.-S. Müller, S. Naknaimueang, M. Schuh, M. Schwarz, J.L. Steinmann
Karlsruhe Institute of Technology, Karlsruhe, Germany

Abstract

The ANKA electron storage ring of the Karlsruhe Institute of Technology (KIT, Germany) is regularly operated in low-alpha mode to produce short bunches for the generation of coherent synchrotron radiation (CSR). This paper evaluates systematic bunch length measurements taken in low-α operation of the ANKA storage ring. Above the bursting threshold not only the emission of CSR occurs in bursts, but also a continuous fluctuation of the bunch's length is observed. The measurements were carried out using concurrent multi-turn (using a streak camera, SC) as well as single-shot (using electro-optical spectral decoding, EOSD) methods. Furthermore, we compare information obtained on the fluctuation to simulations.

INTRODUCTION

For bunch charges above a threshold that depends on beam optics and RF voltage, bursts of CSR are observable. These define the so-called bursting instability. Bunch lengthening is a well known feature of this instability, but measurements have also shown oscillations of the bunch length that had the same periodicity as bursts measured at the same time [1].

There are two challenges one faces when trying to resolve fluctuations of the bunch length in low-α_c operation. First of all, the bunch length goes down to a few picoseconds, so one needs methods that are sensitive enough to resolve the length to sub-ps-accuracy, to be able to see fluctuations. EOSD as well as a SC can fulfill this. Secondly, the bunch length and longitudinal oscillation might have about the same magnitude. So one needs measurements that are not disturbed by the synchrotron oscillation. To meet these requirements, we had to operate the SC to resolve the synchrotron frequency. Doing this, the turn-by-turn fluctuation cannot be resolved directly, so we also did a cross check simulating SC images. Furthermore we compare our results to a simulation of the physics in longitudinal phase space based on the Vlasov-Fokker-Planck equation.

Table 1: ANKA Machine Settings

Circumference	110.4 m
f_s	7.7 kHz
V_{RF}	4×450 kV
Energy	1.3 GeV
Filling pattern	single bunch
Current range	$0.065\,\text{mA} < I < 2.0\,\text{mA}$
Bursting Threshold	$I_{th} \approx 0.07$ mA

* patrik.schoenfeldt@kit.edu

Since all measurements mentioned in this paper were carried out with one single bunch inside the ANKA storage ring, interaction between different bunches does not have to be taken into account. The most important parameters used are shown in Table 1.

FLUCTUATION OF BUNCH LENGTH

Simulation

For the simulation of SC images (MSCI, *Mock Streak Camera Images*) we use bunch length and synchrotron frequency as input, and add realistic noise. The parameterized average bunch length is

$$\bar{l}(I_b) = \sqrt[q]{(l_0)^q + \left(k \times I_b^{3/7}\right)^q} \tag{1}$$

with the bunch current I_b, the natural bunch length l_0 and the empirical fit parameters q and k. Since incoherent light is used for the SC, the number of photons hitting the screen is scaled proportional to I_b. This already allows investigation of statistical influences. As an additional input parameter, here we used the main bursting frequency, as measured using fast THz detectors [2] (see Fig. 1). For the length fluctuation an amplitude of 10 % has been assumed. The simulated images are subjected to the same analyzes chain as the actual measurements.

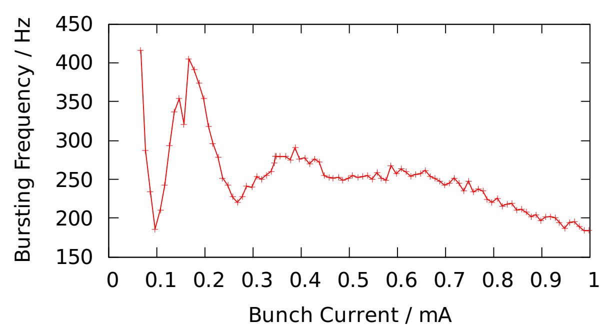

Figure 1: Main frequency at which radiation bursts occur plotted over bunch current. Actual measurement points have been connected to guide the eye. Note that the frequencies are a lot lower than the synchrotron frequency (7.7 kHz), which has to be resolved using the SC. This data is used as input parameter to create MSCI.

This simulation gives an impression of the fluctuation of bunch length that would be measured using the SC. For the bunch length the simulation on the one hand verifies that both sources of noise do not have a big impact on the measurements in the current range we present in this paper. On

ISBN 978-3-95450-132-8

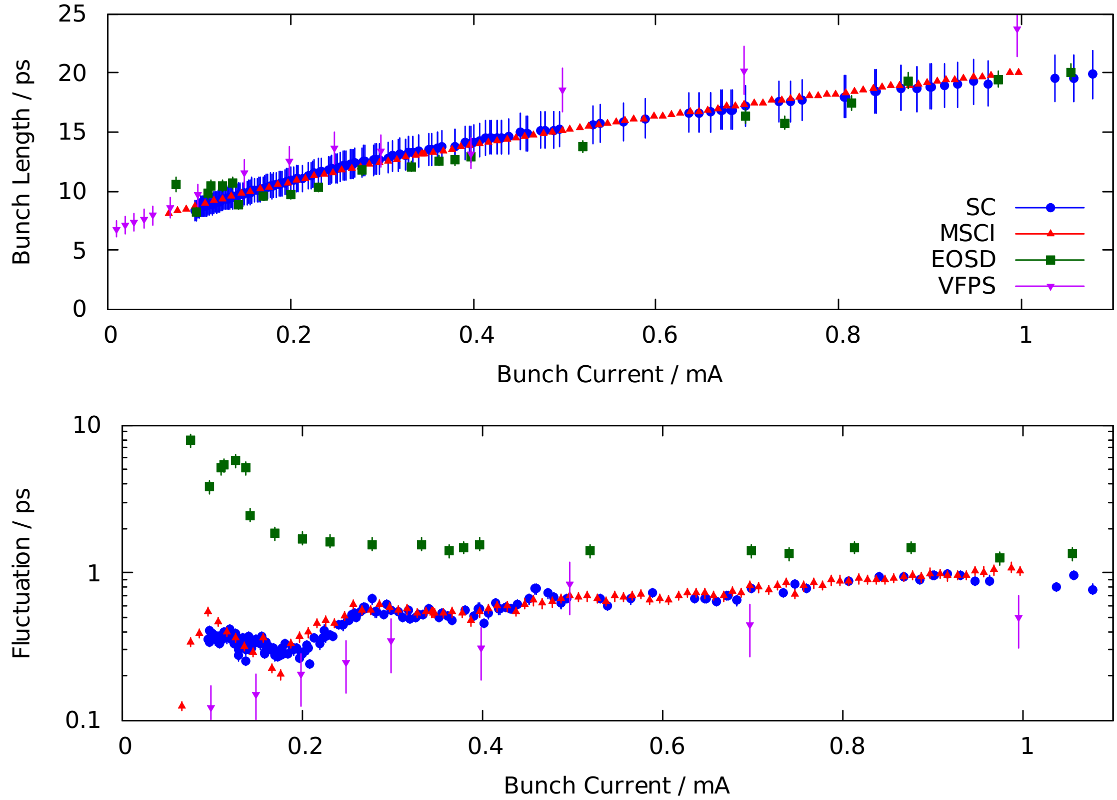

Figure 2: The upper plot shows bunch length (FWHM), the lower plot the fluctuation of bunch length obtained by all used methods. All results agree well. For the fluctuation (lower plot) on the other hand, there are some differences between the methods. The increase in measured fluctuation for low currents obtained using EOSD can be explained by the decreased shot-to-shot accuracy with decreasing electrical field. The MSCI approach which folds bunch length, the SC's time range, and the frequencies of the bursts reproduces the fluctuation directly obtained using the SC very well.

the other hand it gives evidence that the bursting frequency indeed has an impact on the measured fluctuation of bunch lengths. The results are shown in Fig. 2 and will be discussed in the results section.

The Vlasov-Fokker-Planck Solver (VFPS) used for the second simulation was originally implemented by M. Klein [3]. A brief explanation can be found in [4]. As for the MSCI some input parameters are derived from measurement data. The momentum compaction factor α_c and the slip factor η are calculated

$$\alpha_c \approx -\eta \approx \frac{f_s^2 \times 2\pi \times E/e}{f_{rev} \times \dot{V}_{RF}} \tag{2}$$

with the revolution frequency f_{rev}, the time derivative of the RF voltage $\dot{V}_{RF} \approx f_{RF} \times V_{RF,1} = 500\,\text{MHz} \times 450\,\text{kV}$, and the beam energy E. The energy spread σ_E has been derived from the natural bunch length $\sigma_{z,0}$ using

$$\sigma_E = \frac{\sigma_{z,0} \times 2\pi f_s}{\eta c}. \tag{3}$$

The accuracy of the VFPS data is limited by computation time as well as by the accuracy of the input parameters, particularly by $l_0 \approx \sigma_{z,0} \times 2.35 = (6.50 \pm .06 \pm .24)$ ps. Especially for long bunch lengths, a large mesh has to be used. So only a limited number of synchrotron periods can be simulated in reasonable computation time, which means that statistics for the fluctuation is not optimal. Currently the number of simulated bursts is $N = 50$.

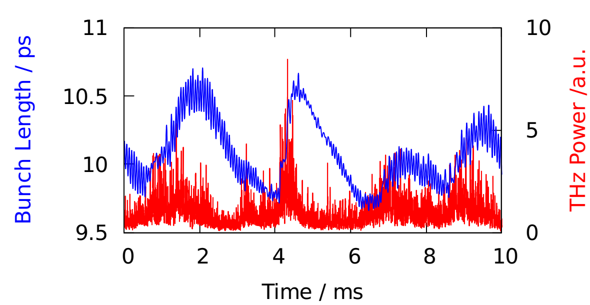

Figure 3: Example for a solution of the Vlasov-Fokker-Planck equation. At the time the bunch length (RMS × 2.35, blue, left axis) starts to increase, the CSR (red, right axis) is bursting. When the CSR intensity drops, the bunches to shortens again.

The qualitative result that correlates bursting CSR with fluctuations in the bunch length – as seen in Fig. 3 – agrees

ISBN 978-3-95450-132-8

well with the expectations: The bunch length is correlated to the emitted CSR power, both quantities fluctuate at the same frequency. While the frequency itself deviates from the measurements by a factor of about 2.5 (see also [4]), the pattern of the THz power looks similar to measured intensity fluctuations.

As for the MSCI, the results for the average bunch length as well as for the length fluctuation are shown in Fig. 2 and will be discussed in the results section.

Measurements

To measure bunch length and longitudinal profile we mainly use two methods. The used SC, a Hamamatsu C5680, has dual sweep which allows to record a bunch's profile continuously over time. Since we are interested in accurate measurements for short bunches, the amplitude of the synchrotron oscillation has to be taken into account. Hence the (slow) time axis has to be chosen in a way that the synchrotron oscillation is clearly visible. We then are able to deduct it and get an (averaged) bunch profile from the projection onto SC the position (fast time) axis. According to benchmarks using MSCI for constant bunch lengths this method gives an accuracy which is better than $\Delta l_{SC} < 0.3\,\mathrm{ps}$.

Additionally we do near field measurements using electro optical spectral decoding [5] to obtain the electron bunches' profile in a single pass-by. The statistical uncertainty of this method is limited by the field strength, thus can vary shot by shot depending on the distance between beam and electro-optical crystal. Furthermore there is a timing-dependent bias which in the worst case adds a deviation of up to one third (peak to peak) for bunch length. Thus the uncertainty for a single shot is $\Delta l_{EO} = 10\,\%$.

Discussion and Results

All measurement results (as well as simulation results) are shown and compared in Fig. 2. Note that the (average) bunch length $\bar{l}$ obtained with both measurement methods agrees well (upper plot), but the standard deviation of the distributions

$$\sigma_l = \sqrt{\frac{1}{N-1}\Sigma_i^N \left(\bar{l} - l_i\right)^2} \tag{4}$$

(lower plot) show significant differences. For the values obtained by EOSD, there is an increase for currents below 0.3 mA, which can be explained by a very low signal to noise ratio. For any other case (real) fluctuation of the actual length give an important contribution to σ_l. The fact that streak camera measurements show lower values for the fluctuation can be explained by the averaging that even plays a role for slow burst: The slow time axis was set to 1 ms, the fastest fluctuation always happens with $f_s = 7.7\,\mathrm{kHz}$ (cf. Fig. 3).

All results obtained for the bunch length (see upper plot in Fig. 2) match very well. There is a slight tendency that the EOSD's average length is smaller than the one obtained by the SC. A possible explanation is that the single SC lengths are deducted from bunch profiles averaged over 1 ms.

For the fluctuation of bunch length (see lower plot in Fig. 2) the MSCI using bursting frequencies as input parameters match the real SC measurements almost perfectly. The VFPS data also agrees within the uncertainty estimation. As one would expect, the fluctuation decreases when the current is near the bursting threshold. The EOSD measurements for the lower currents ($I_b < 0.3\,\mathrm{mA}$) are influenced by a bad shot-to-shot accuracy. For the higher currents the EOSD results are larger but in the same range as the ones obtained using the SC. This feature is expected because of the averaging in every SC image. Also note that the change in the fluctuation obtained by SC is mainly caused by the changing bursting frequency: While over a wide current range the bunch length changes proportional to $I^{3/7}$, the measured fluctuation changes exponentially.

CONCLUSION AND OUTLOOK

This paper has presented both simulations and systematic measurements of the length of bunches above the bursting threshold. It has been shown that the bunch length fluctuates with the main frequencies of the THz bursts. Since at the SC the bursting frequency plays a big role when measuring length fluctuations, even a simple model for the amplitude gives sufficient results. Optimizations at the EOSD setup and continued work on the VFPS will help to also find a more accurate model for the fluctuation amplitude.

ACKNOWLEDGMENTS

We would like to acknowledge the ANKA infrared group for allowing access to the IR1 and IR2 beam lines.

Work supported by the Initiative and Networking Fund of the Helmholtz Association (Grand No. VH-NG-320), the German Federal Ministry of Education and Research (Grant No. 05K10VKC and 05K13VKA) and by the Helmholtz International Research School for Teratronics (HIRST).

REFERENCES

[1] Y.-R. E. Tan et al. "Low Alpha Configuration For Generating Short Bunches", PAC 2009, TH6PFP009.

[2] Advanced Compound Semiconductor Technologies GmbH, Merckstr. 25, D-64283 Darmstadt, Germany; www.acst.de

[3] M. Klein "Optics Calculations and Simulations of Longitudinal Beam Dynamics for the Low-alpha Mode at ANKA", Verlag Dr. Hut, München.

[4] V. Judin et al. "Bursting Patterns of Coherent Synchrotron Radiation in the ANKA Storage Ring", IPAC 2013, WEPEA011.

[5] N. Hiller et al. "Status of Single-Shot EOSD Measurement at ANKA", IPAC 2014, WEOBB02.

ISBN 978-3-95450-132-8